Galaxies for cosmologists

David W. Hogg
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random tribute

Gerry Neugebauer

- one of the first people to point an infrared detector at the sky (and there were many nay-sayers)
- PI of IRAS, one of the most productive NASA missions ever
- taught me (almost) everything I know about *astronomy*, *ie,* observational astrophysics

about this review

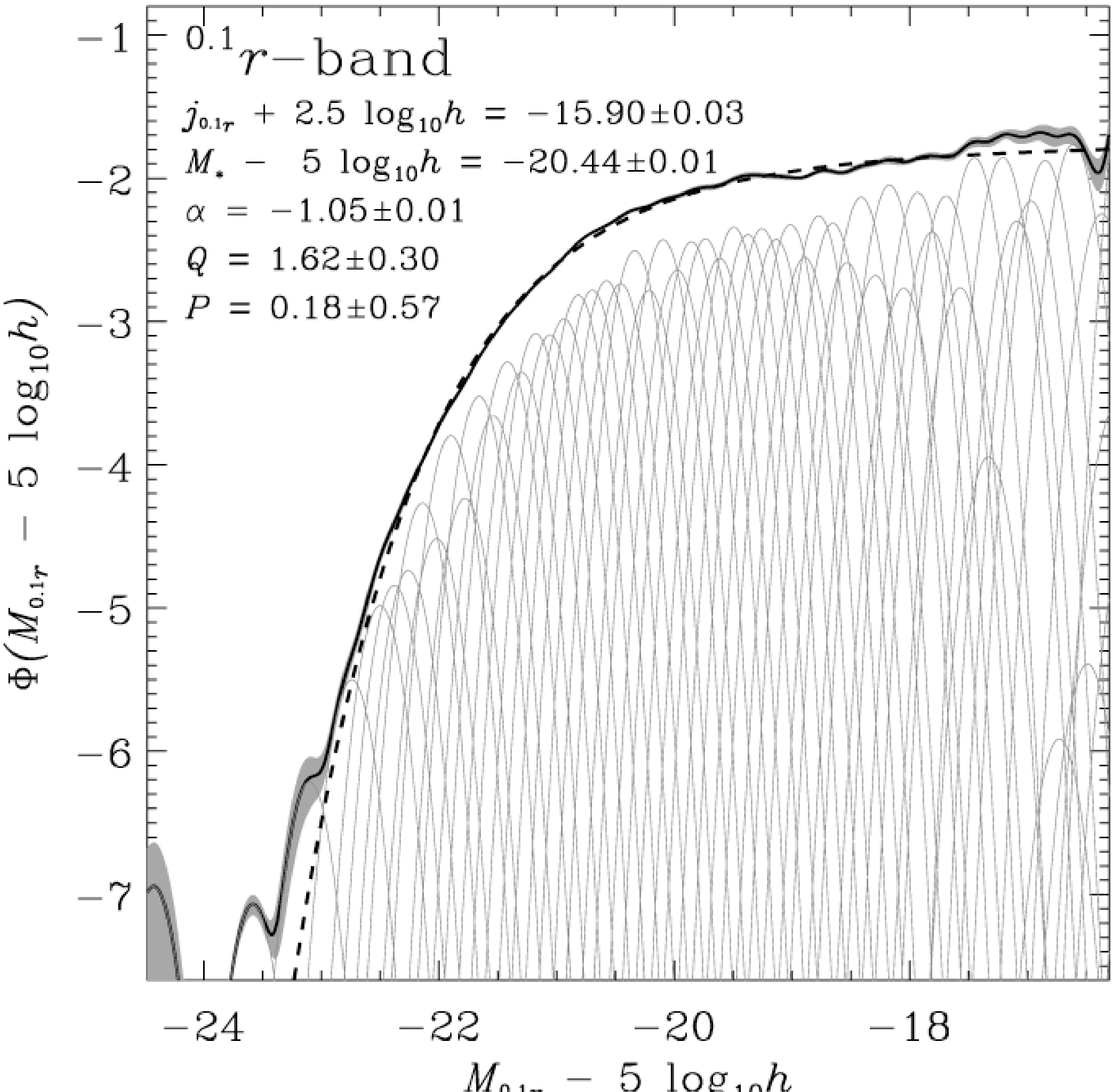
- I will give no credit, even when it is due.
- I will be insulting to my colleagues and audience.
- Otherwise, this review will be absolutely *fair and balanced.*

David W. Hogg does and seeks to do business with some of the ideas covered in this review. As a result, the audience should be aware that he may have a conflict of interest that could affect the objectivity of this review. The audience should consider this review as only a single factor in making their scientific and professional decisions.

Numbers

- There are about 10^{10} L*-ish galaxies in the Hubble Volume.
- There are about 10^{11} Solar-ish stars in each L*-ish galaxy.
- Galaxies represent overdensities of $\sim 10^9$ (formation starts at $z \sim 1000$?).

Blanton et al. (2003) (astro-ph/0210215)



editorial comment

Theory

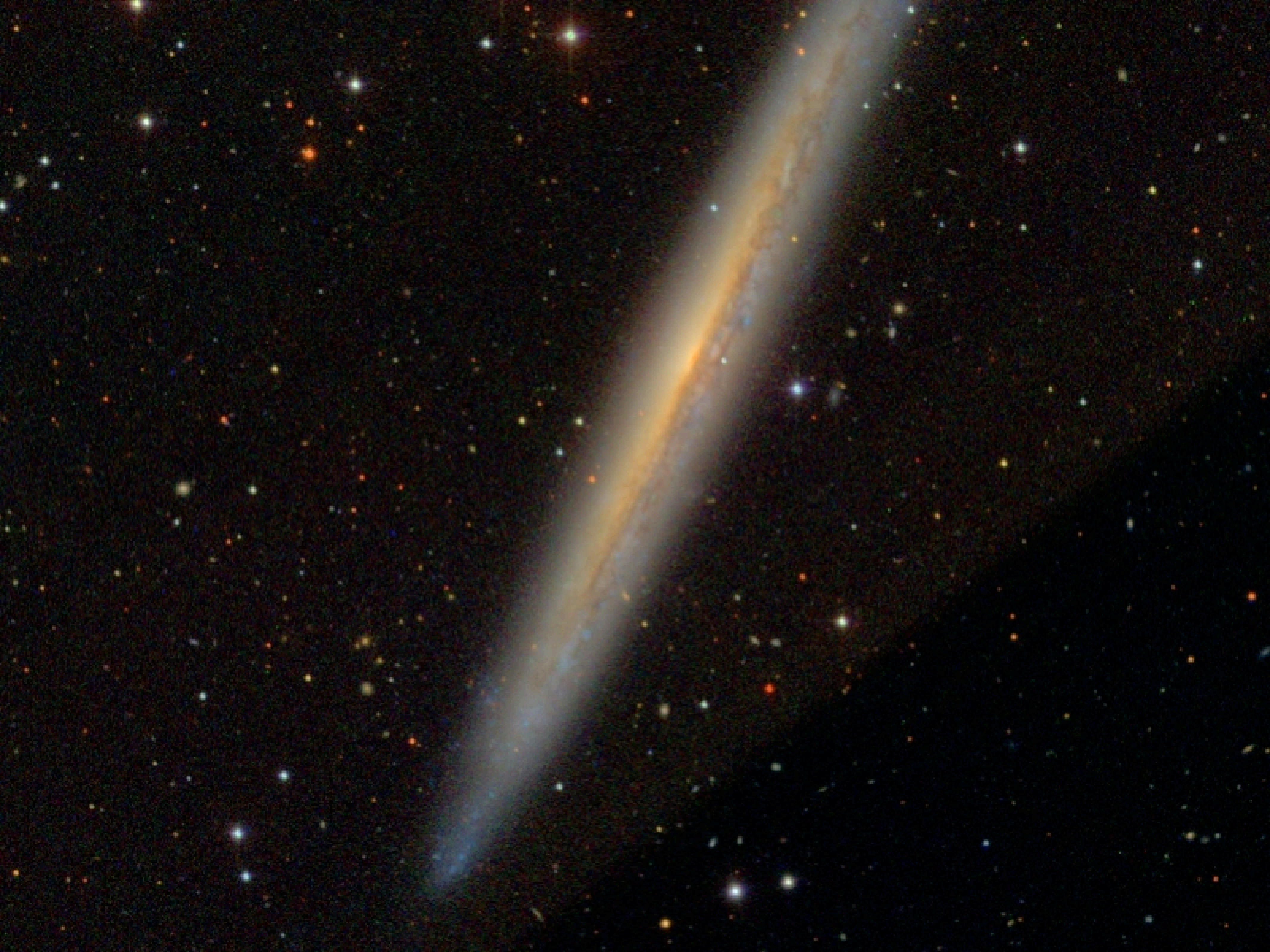
- We don’t even understand the galaxy luminosity function!

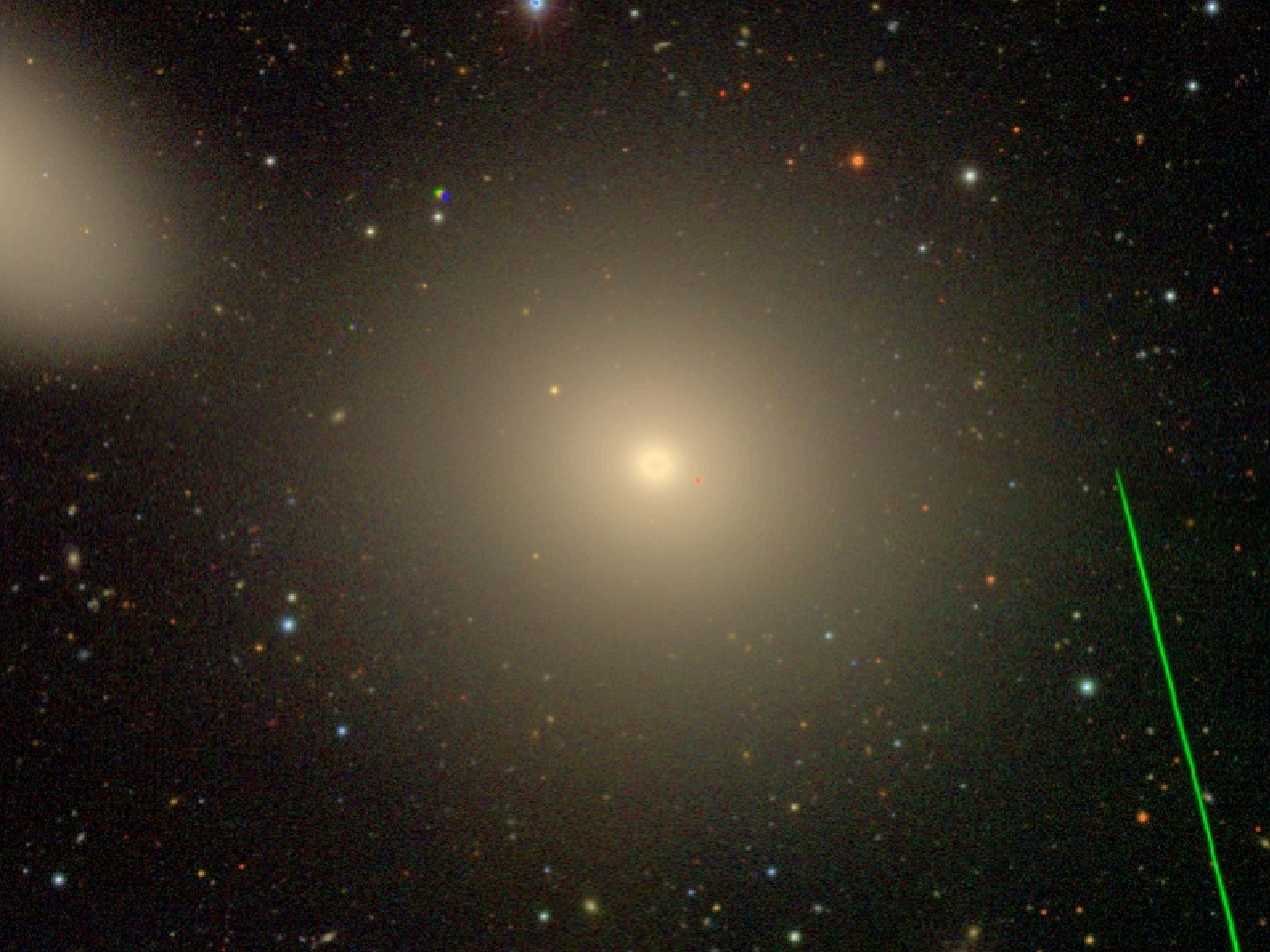
Time-scales

- The Hubble time: $t_H \sim 10^{10}$ yr
- typical dynamical time: $t_{dyn} \sim 10^8$ yr
- time to for stellar populations to "look old": $t_{old} \sim 10^9$ yr

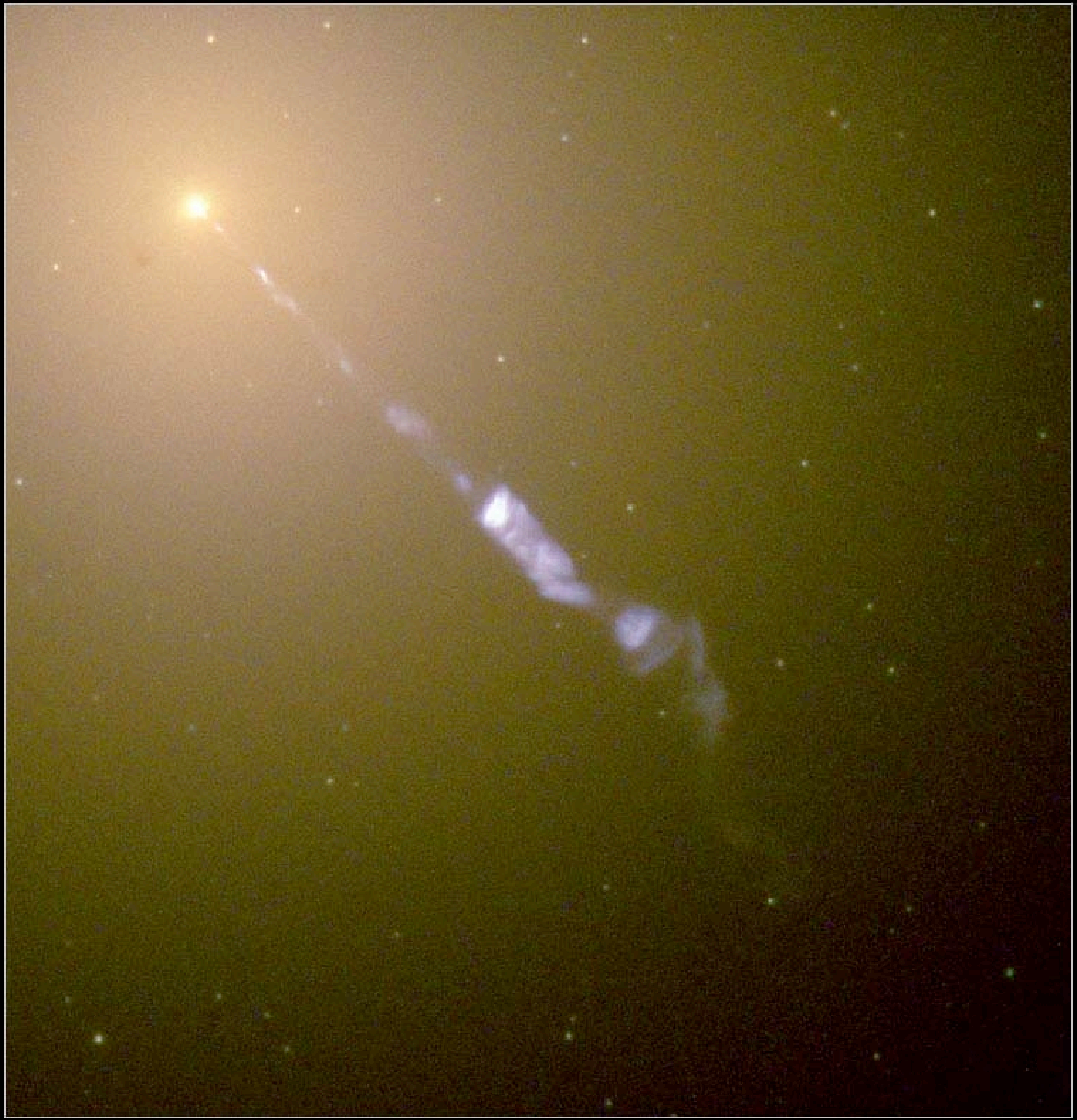
Contents

- 85 percent dark matter
- 15 percent baryons, of which 90 percent are in a warm plasma state
- fractions depend strongly on radius
- *editorial comment:* Most of the matter, and even most of the baryons, is only observed *very indirectly.*

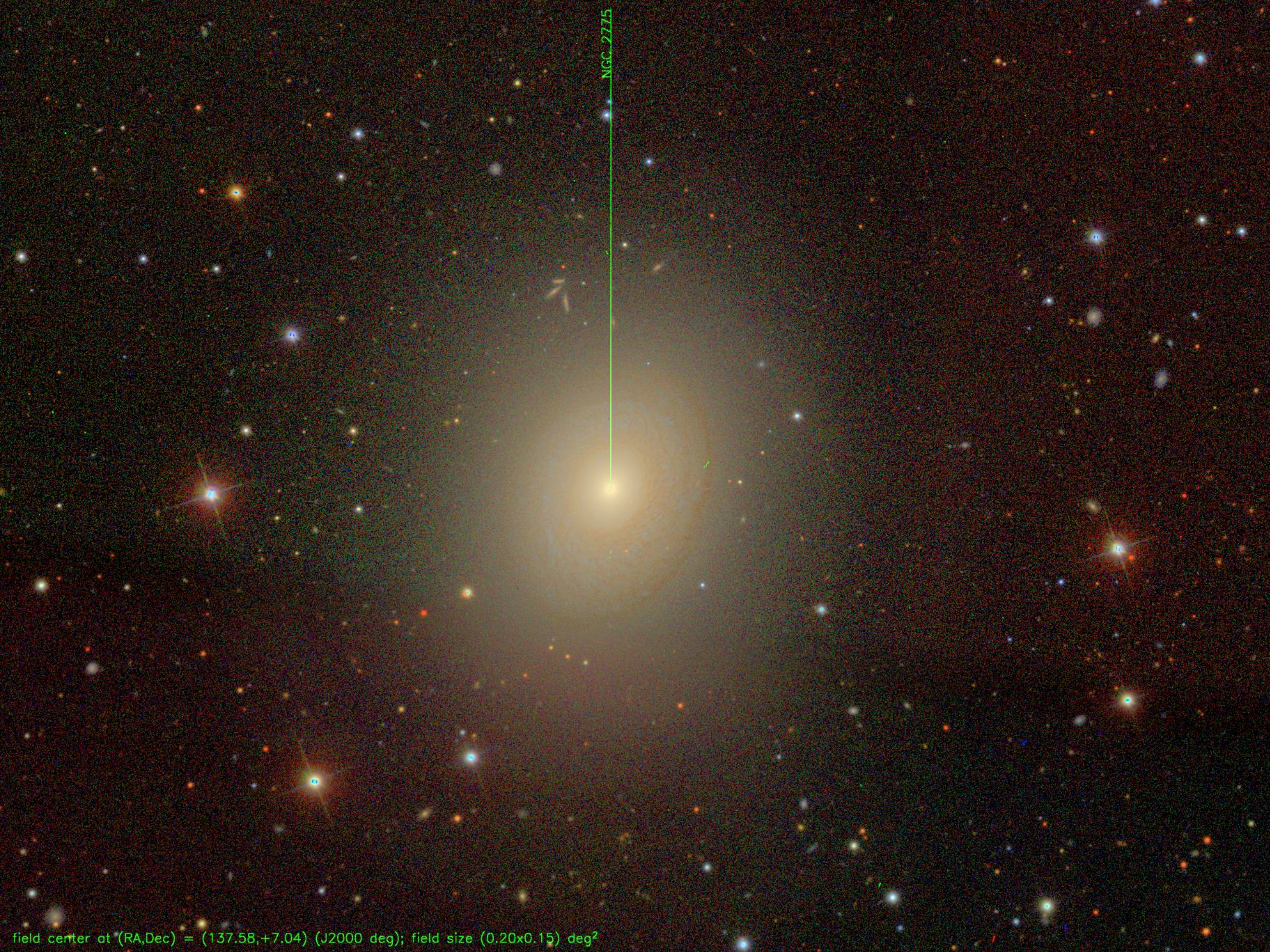


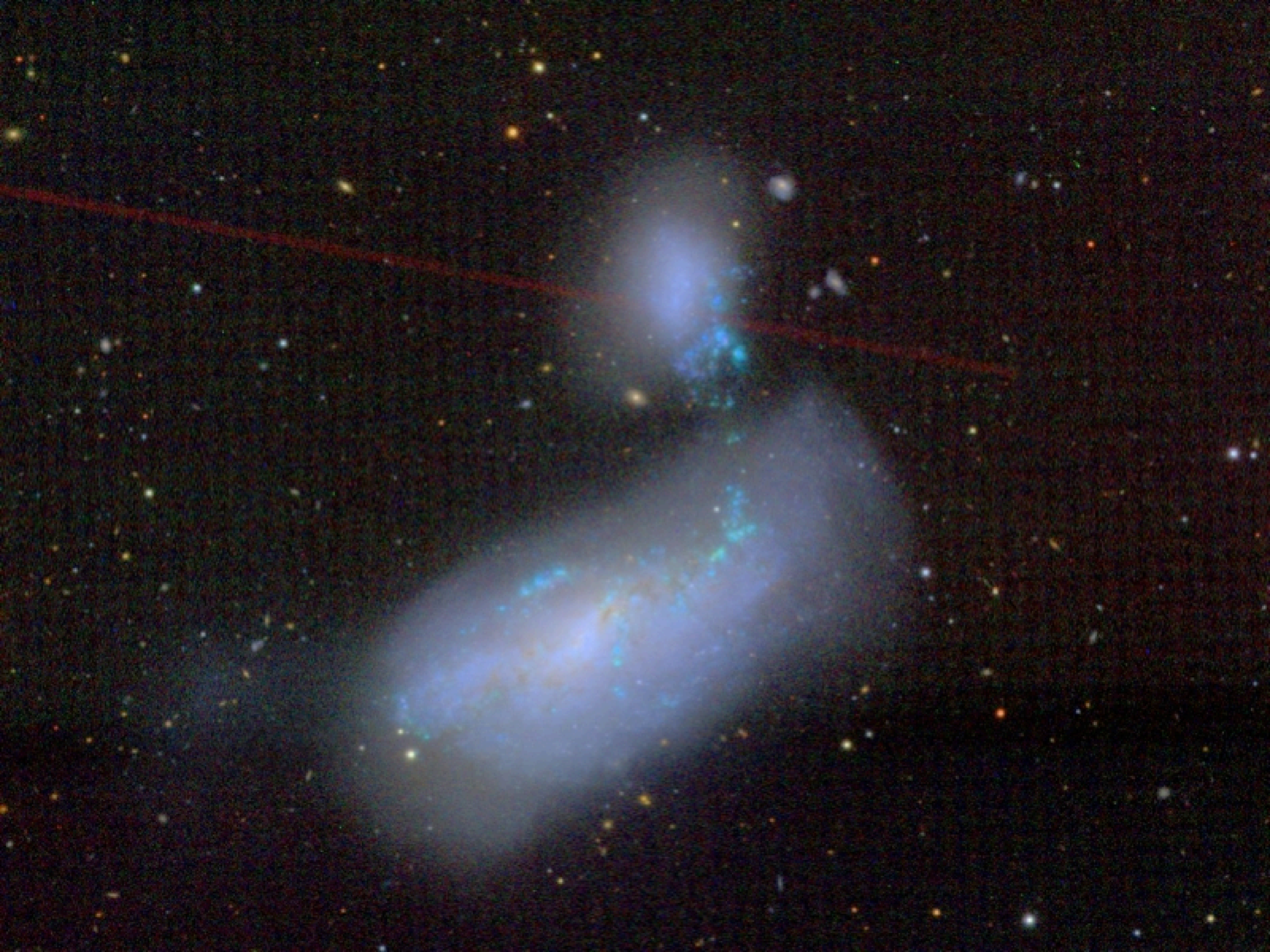


The M87 Jet



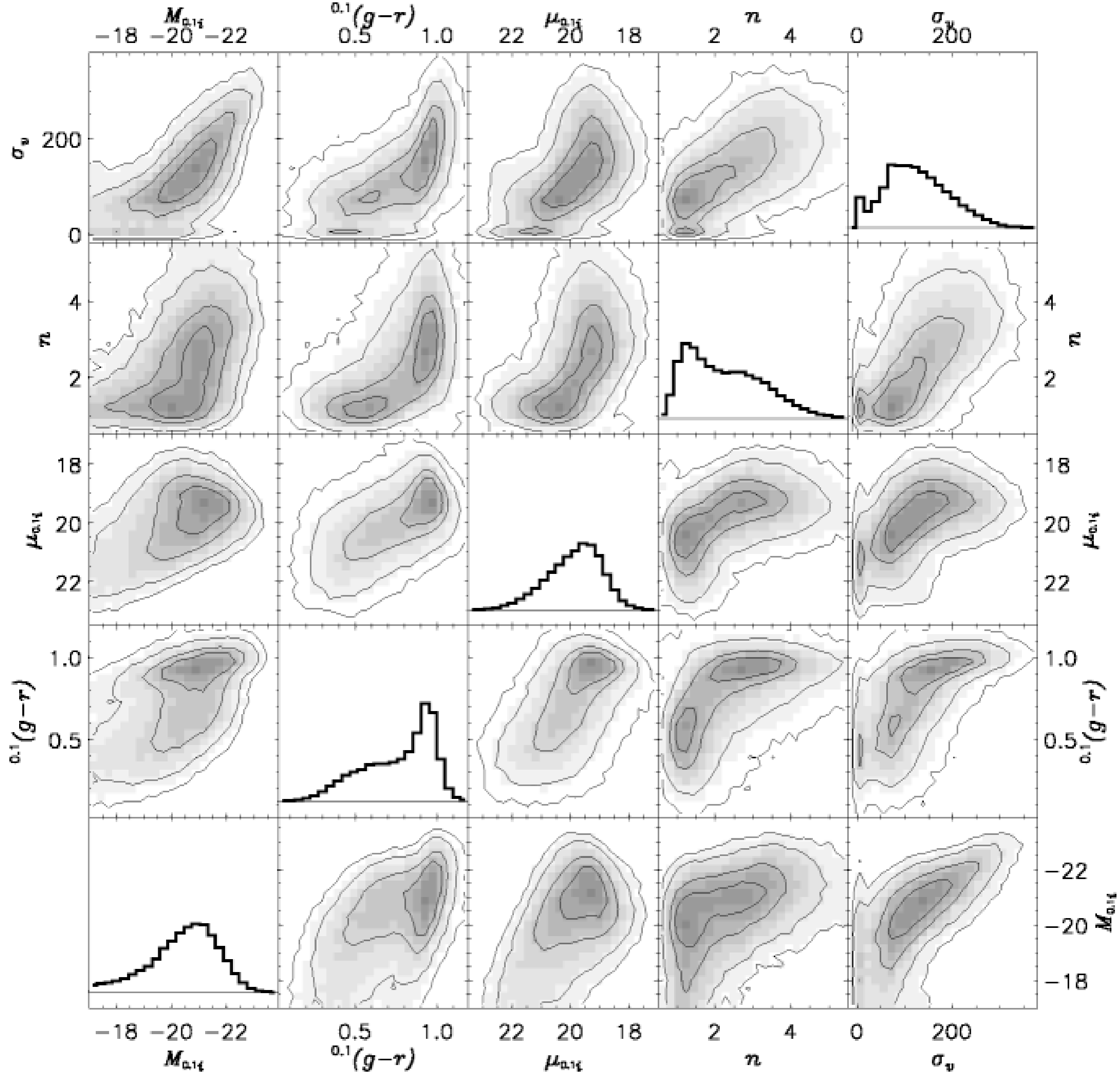
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)


NGC 2775
field center at (RA,Dec) = (137.58,+7.04) (J2000 deg); field size (0.20x0.15) deg^2

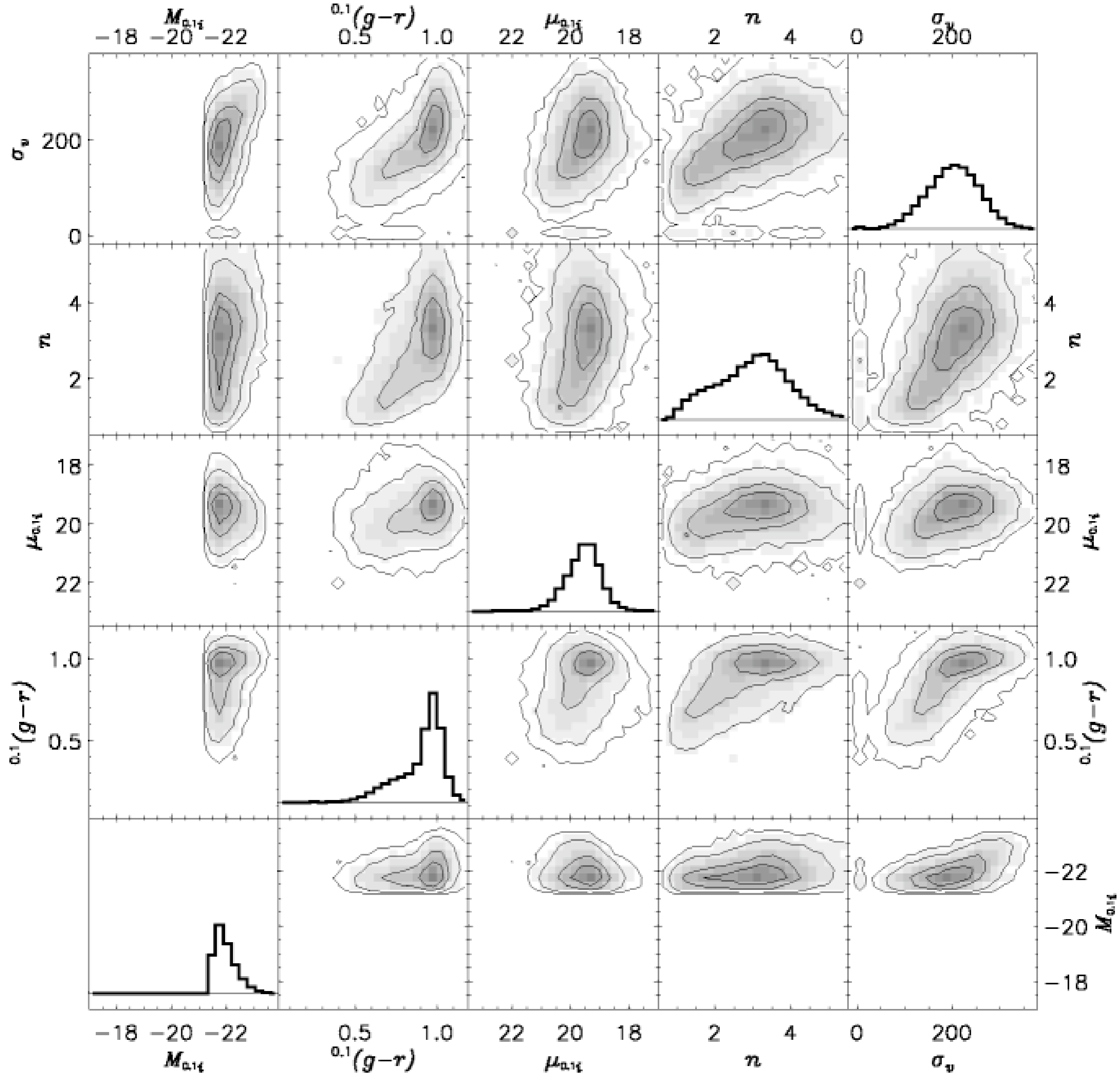


Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA



$M_{0.1i}$
$^{0.1}(g-r)$
$\mu_{0.1i}$
n
σ_v



$M_{0.1i}$
$^{0.1}(g-r)$
$\mu_{0.1i}$
n
σ_v

Bulge-dominated galaxies

the *minimum* you need to know

- “early type”-“elliptical”-“lenticular”-“dynamically hot”-“*ugh*”
- dead; only DM, warm plasma, and old stars
- alpha-enhanced
- very dense centers
- contain super-massive black holes
- show surprising and *informative* regularities
- over-represented in high-density environments

Disk-dominated galaxies

the *minimum* you need to know

- “spiral”
- have gas, dust and ongoing star-formation
- We live in one (known as the *Milky Way*) and it appears typical in every respect.

Hubble Classification

the *minimum* you need to know

- based on radial profile and spiral arm strength, winding angle, irregularity, and *flocculence*.
- Hubble class correlates with essentially all known galaxy properties.
- It is not objective, in the strict sense.
- *editorial comment:* Work with physical properties, not "classes".

editorial comment

CDM is *not* the last word

- CDM is very well tested (and confirmed!) on scales >10 Mpc.
- There are **no** precise tests on 10 Mpc scales or smaller.
- An understanding of galaxies is absolutely necessary to reach these scales.
- It strains credulity to even *hypothesize* that there is *no complexity* in the dark sector.

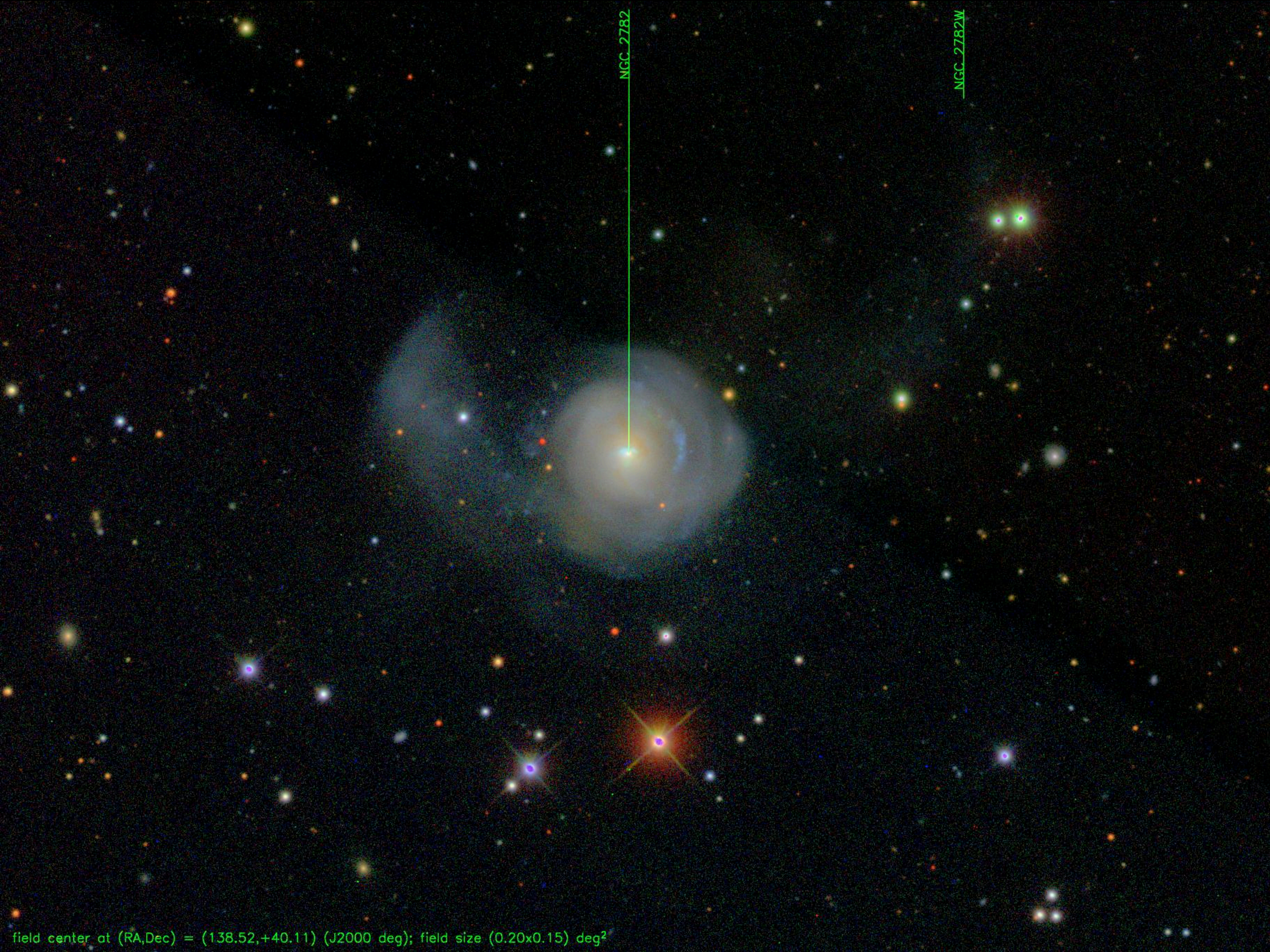
but

- from now on, I will accept all the predictions of CDM with fawning credulity!

[coffee?]

Merging

- In the dark sector, smaller things form first, and they merge to make larger things.
- This process continues to the present day.
- Galaxies are inside these merging dark-matter clumps.
- Merging ought to be the essential process of galaxy evolution.


NGC 2782
NGC 2782W
field center at (RA,Dec) = (138.52,+40.11) (J2000 deg); field size (0.20x0.15) deg²

Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA

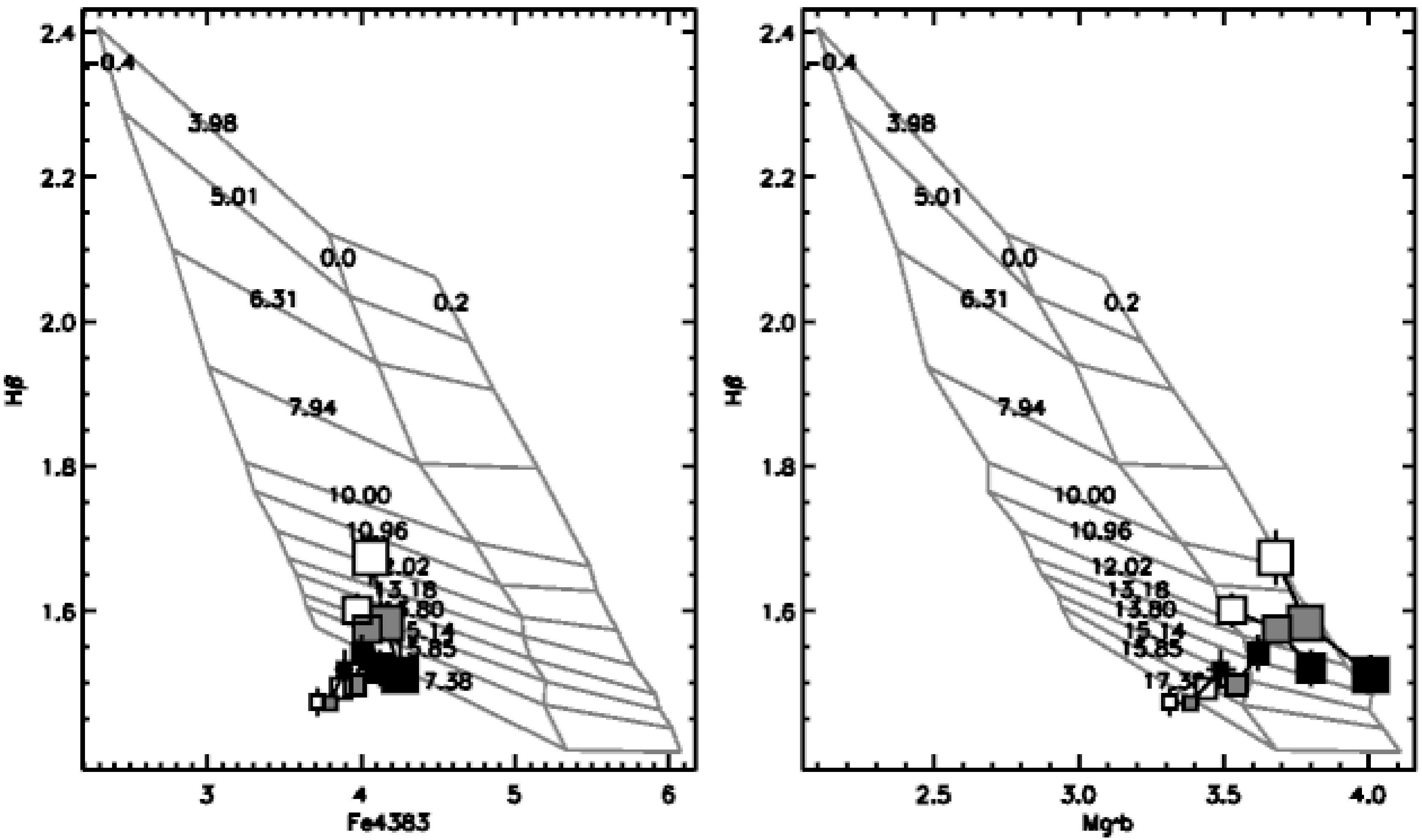
warning

- Determination of the merger rate by *morphological means* is fraught with danger.
- Not all close pairs will merge *soon*.
- Tidal features are visible for unknown periods, and the periods depend on galaxy type and environment.
- Irregular morphologies are even less reliable than tidal features.

Chemical enrichment

the *minimum* you need to know

- Type Ia supernovae (which produce Fe) do not start going off until 10^9 or more years after star formation begins.
- Other SNe types produce mainly "alpha" elements, and start to explode promptly after the beginning of star formation.
- "Alpha-enhanced" stellar populations can only be produced in *rapid bursts*.



Hβ
2.4
2.2
2.0
1.8
1.6
-0.4
3.98
5.01
0.0
6.31
0.2
7.94
10.00
10.96
13.18
3
4
5
6
Fe4383
Hβ
2.4
2.2
2.0
1.8
1.6
-0.4
3.98
5.01
0.0
6.31
0.2
7.94
10.00
10.96
12.02
13.18
13.80
15.14
15.85
2.5
3.0
3.5
4.0
Mg b

editorial comment

Merging

- Each galaxy type has characteristic chemical abundance patterns and central stellar densities.
- You cannot randomly merge galaxies of one type to produce a galaxy of another type!
- If "spirals merge to make ellipticals," something *else* has to happen in the merger events: a strong, short-lived, central star-burst.

warning

- Everything we know about stellar populations, star formation histories, chemical abundances, and supernova enrichment is based on extremely difficult and complicated modeling.
- stellar exteriors, stellar interiors
- The models are *known* to be wrong in detail.

warning

- Now we are going to talk about stars.

Stars

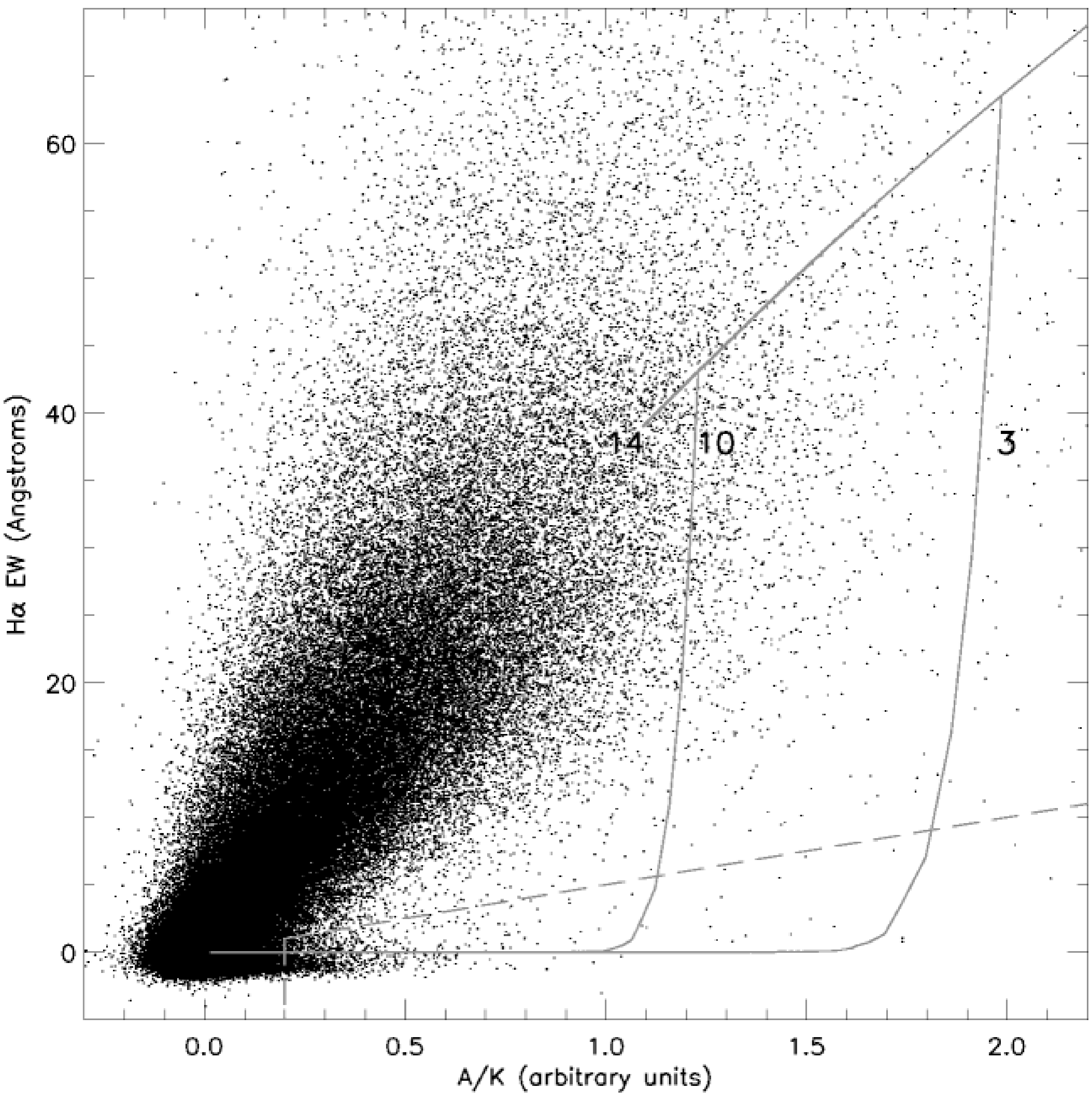
the *minimum* you need to know

- temperature sequence OBAFGKMLT
- main sequence *vs* giants
- Most of the *stars* in a typical galaxy are main sequence, but most of the *light* comes from K giants.
- Very hot (OBA) stars are great tracers of evolution.

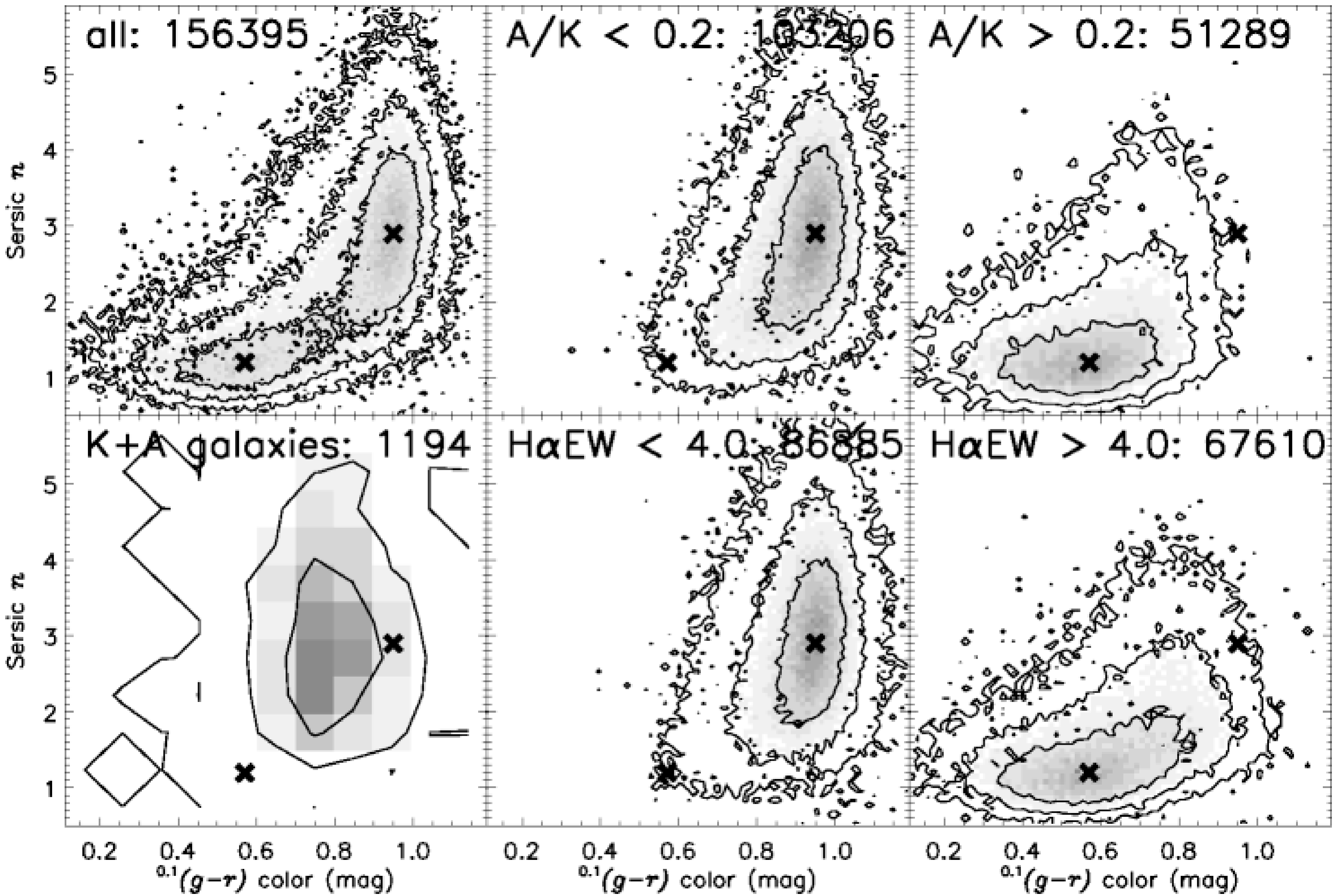
Hot stars

the *minimum* you need to know

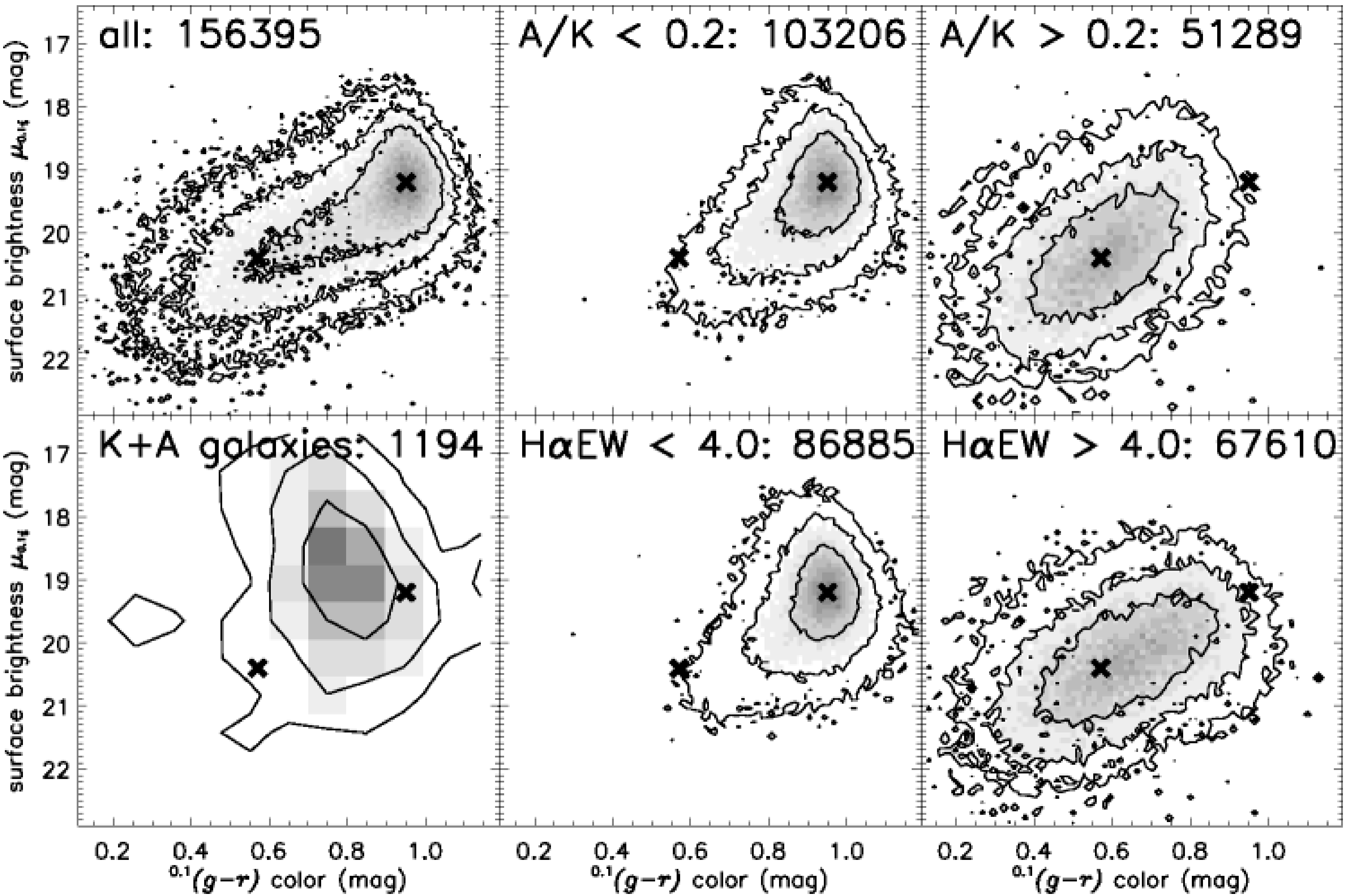
- OB stars are so hot they ionize their environments.
- OB stars live for 10^7 years, *ie*, 0.1 $t_{\rm dyn}$.
- A stars nearly ionize hydrogen, so they show strong Balmer (n=2) absorption.
- A stars live for 10^9 years, *ie*, 0.1 $t_{\rm H}$.



Hα EW (Angstroms)
A/K (arbitrary units)
0
20
40
60
0.0
0.5
1.0
1.5
2.0
14
10
3



all: 156395
A/K < 0.2: 103206
A/K > 0.2: 51289
K+A galaxies: 1194
HαEW < 4.0: 86885
HαEW > 4.0: 67610
Sersic n
$^{0.1}(g-r)$ color (mag)



all: 156395
A/K < 0.2: 103206
A/K > 0.2: 51289
K+A galaxies: 1194
HαEW < 4.0: 86885
HαEW > 4.0: 67610
surface brightness $\mu_{0.1i}$ (mag)
$^{0.1}(g-r)$ color (mag)
17
18
19
20
21
22
0.2
0.4
0.6
0.8
1.0

K+A galaxy conclusions

- event rate: $\sim 10^{-4}\ h^{3}\ \mathrm{Mpc}^{-3}\ \mathrm{Gyr}^{-1}$
- The bulge-dominated galaxy population is growing by 1 percent per Gyr.
- [Quintero et al, 2004, ApJ]
- This *might* be a spiral-spiral merger rate!
- Determination of the merger rate by *morphological means* is fraught with danger.

editorial comment

Galaxy evolution

- Galaxies show much less evidence of evolution and merging that one would naively expect.
- It is very difficult to get unassailable evidence of significant accretion (for the bulk of galaxies).

The study of evolution

- Compare low-redshift and high-redshift populations, accounting for all selection effects.
- Study high-quality fossil evidence in the chemistry and kinematics of the Milky Way itself (or M31 *etc*).
- Study lower-quality fossil evidence in vast numbers of nearby galaxies (from, *eg*, SDSS).

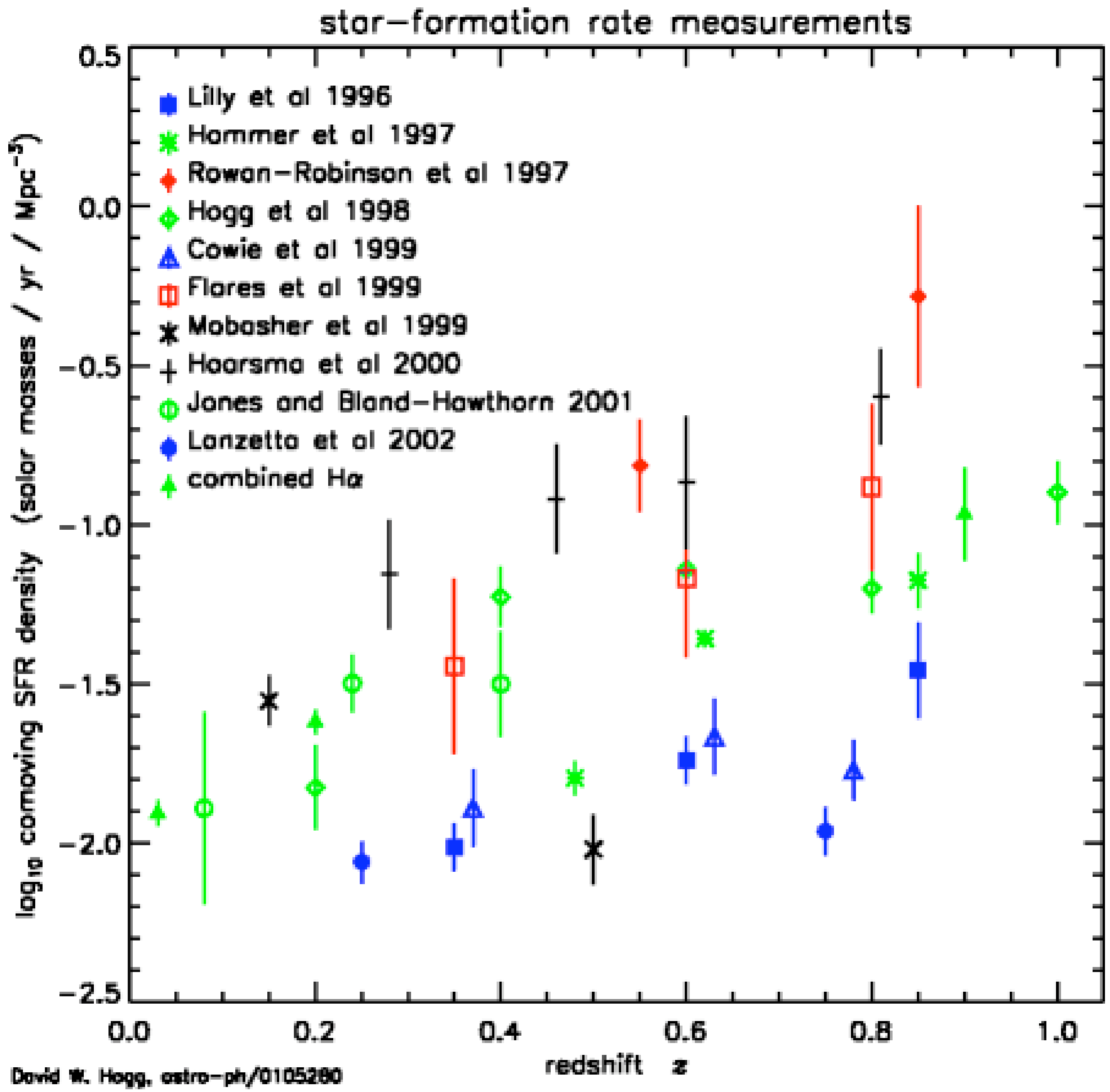
warning

- The three methods *must* give the same answer, unless we are doing something wrong.
- The three methods do *not* give the same answers on all questions!

Galaxies at redshift one

the *minimum* you need to know

- About 10^{10} years ago.
- Similar (comoving) number density of galaxies to the present day.
- Galaxies appear more ragged (perhaps).
- Galaxies show much higher star-formation rates than those at the present day.


star-formation rate measurements
Lilly et al 1996
Hammer et al 1997
Rowan-Robinson et al 1997
Hogg et al 1998
Cowie et al 1999
Flores et al 1999
Mobasher et al 1999
Haarsma et al 2000
Jones and Bland-Hawthorn 2001
Lanzetta et al 2002
combined Hα
log₁₀ comoving SFR density (solar masses / yr / Mpc⁻³)
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
0.0
0.2
0.4
0.6
0.8
1.0
redshift z
David W. Hogg, astro-ph/0105260

The Milky Way

the *minimum* you need to know

- L*
- The disk is very very thin.
- The thin disk contains old (~10^{10} yr old) stars
- The star-formation rate in the Solar neighborhood has been relatively constant over this time period.
- The bulge is alpha-enhanced relative to the disk, and older.

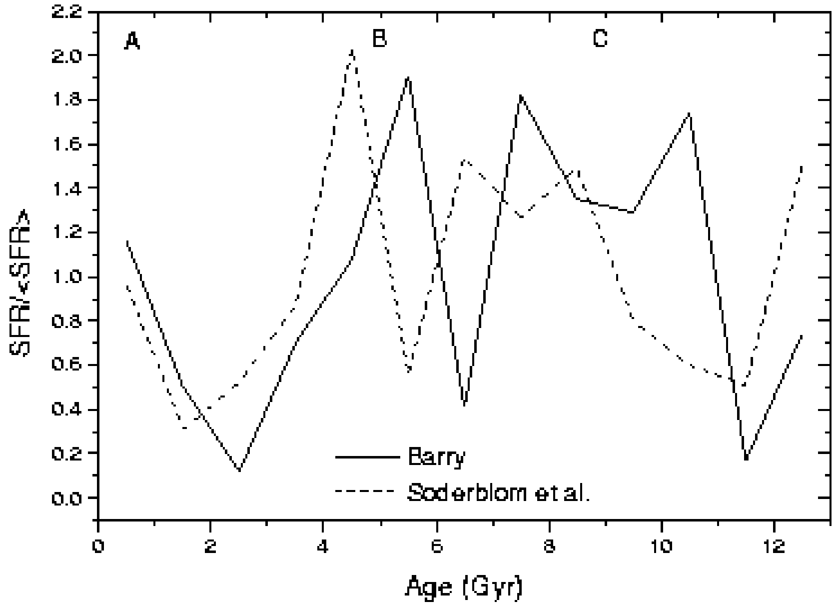


Fig. 6. Comparison between chromospheric SFHs published in the literature: Barry (1988, according to Noh & Scalo 1990) and Soderblom et al. (1991, according to Rana & Basu 1992). The position of bursts A, B and C (named after Majewski 1993) are marked.

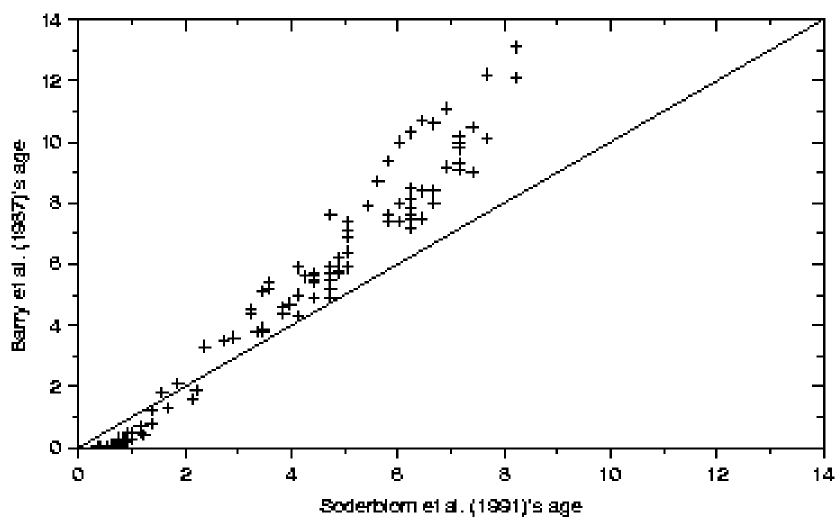


Fig. 7. Comparison of stellar ages (in Gyr) in the calibrations by Barry et al. (1987)'s and Soderblom et al. (1991). The first age calibration

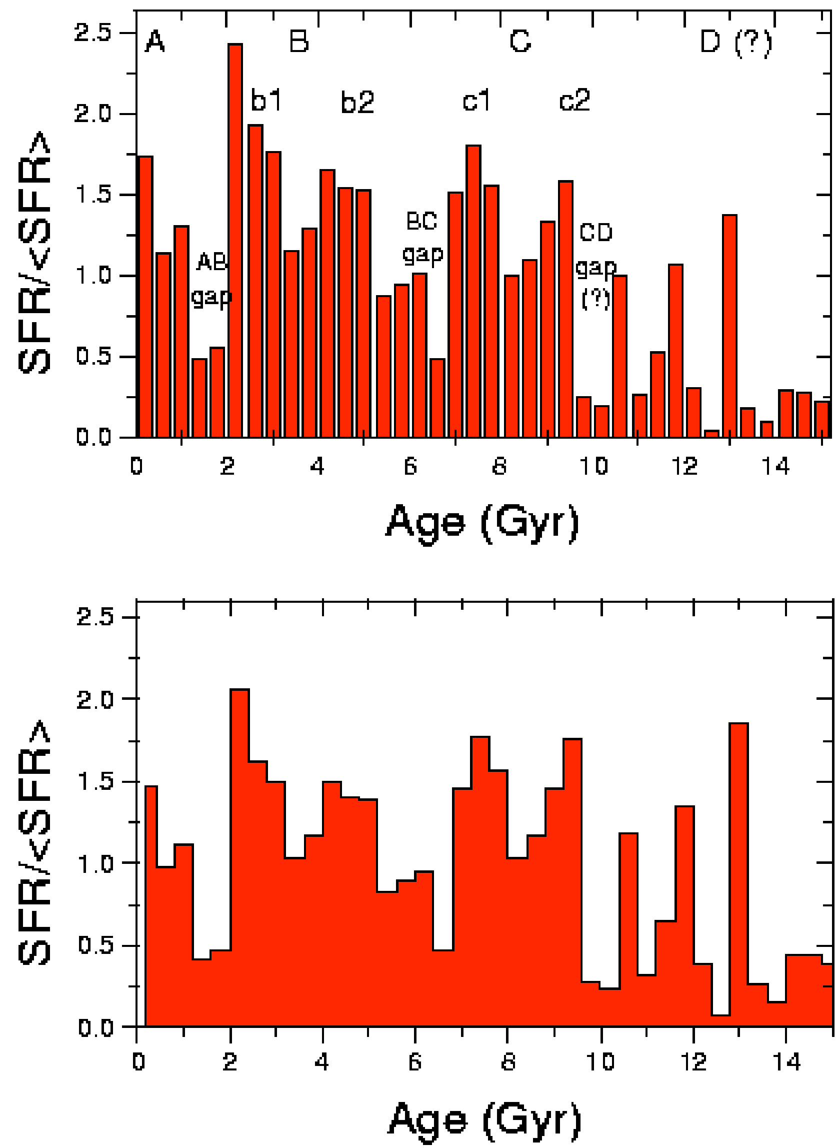
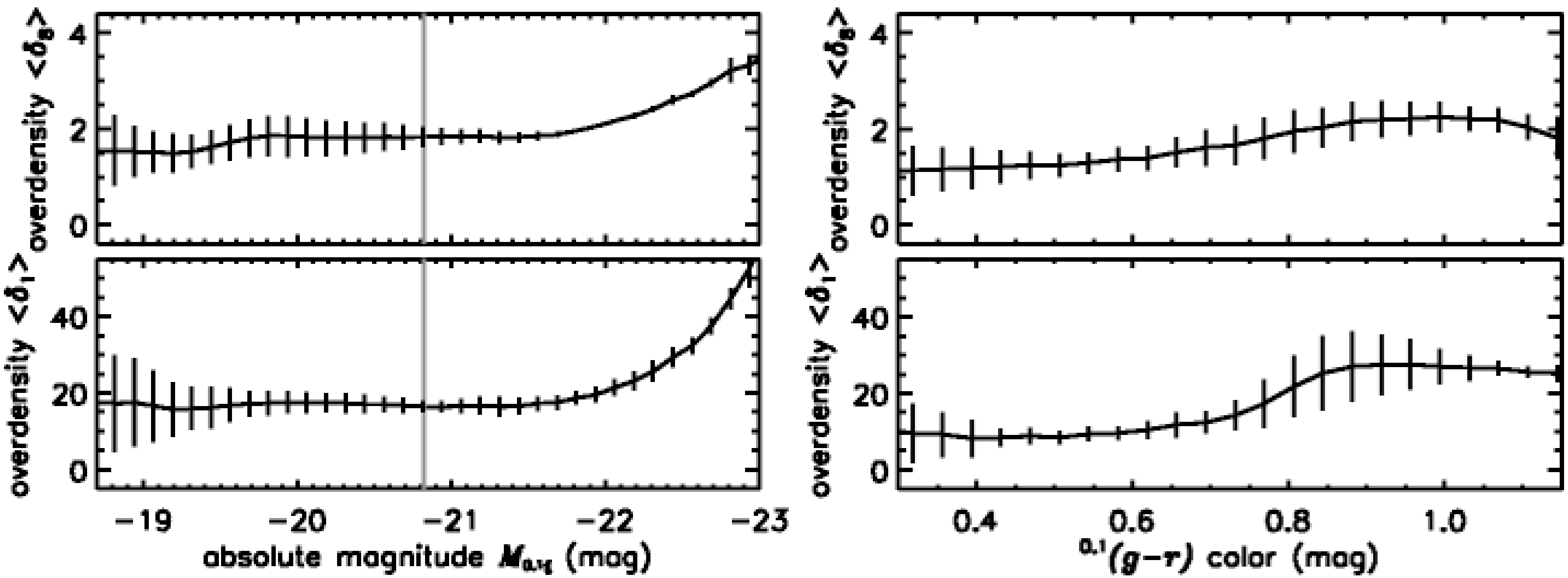


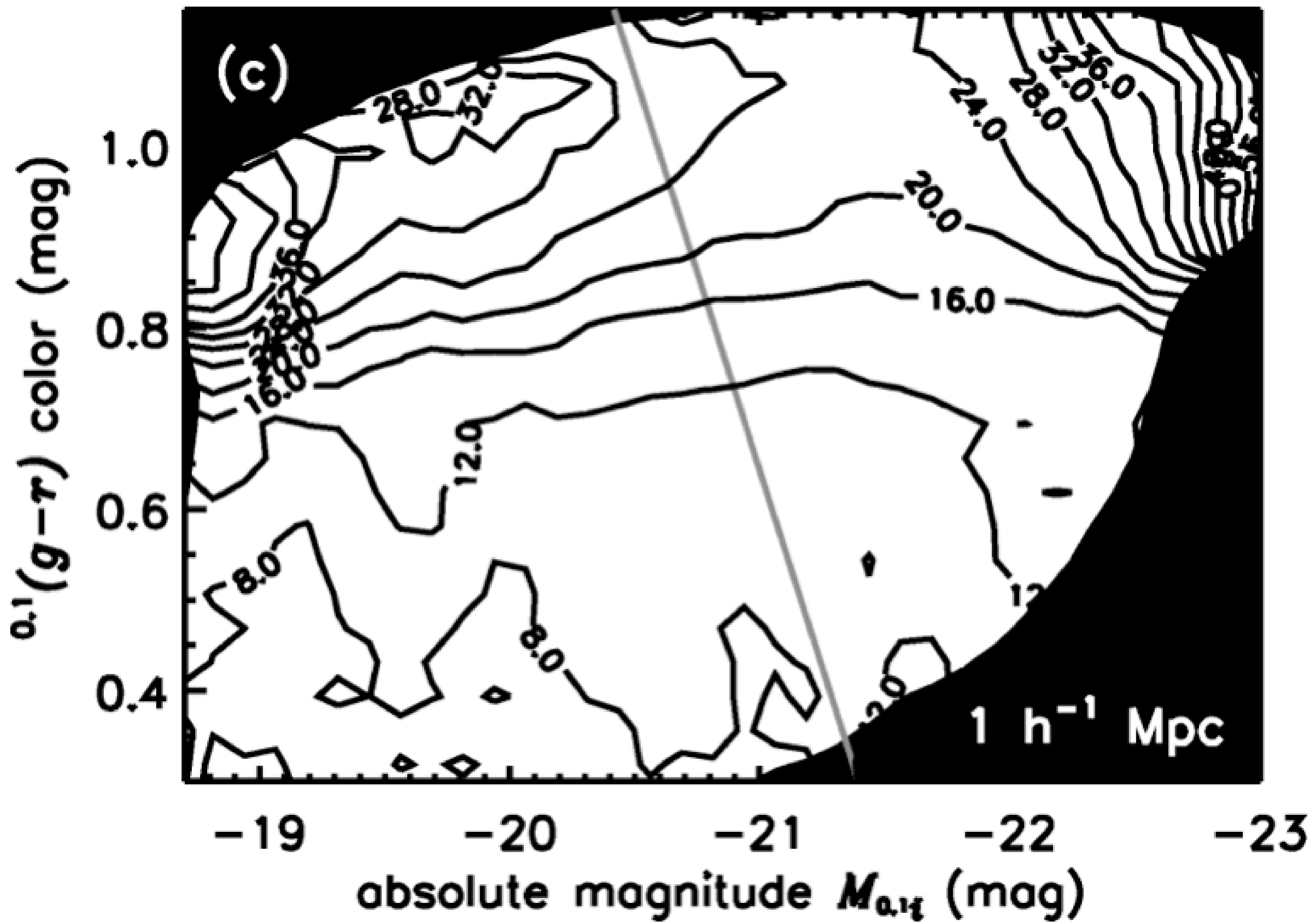
Fig. 8. Star formation rate for an age bin of 0.4 Gyr. The nomenclature used by Majewski (1993) was extended to be used with the main features of the SFH. The terms B1 and B2, and C1 and C2, stand for substructures of the supposed bursts B and C, respectively. Also shown is the supposed burst D. The gaps between the peaks are named AB gap, BC gap, and so on. The upper and lower panels show the SFH using Scalo (1986) and Holmberg & Flynn (2000) scale heights, respectively.

Galaxy environments

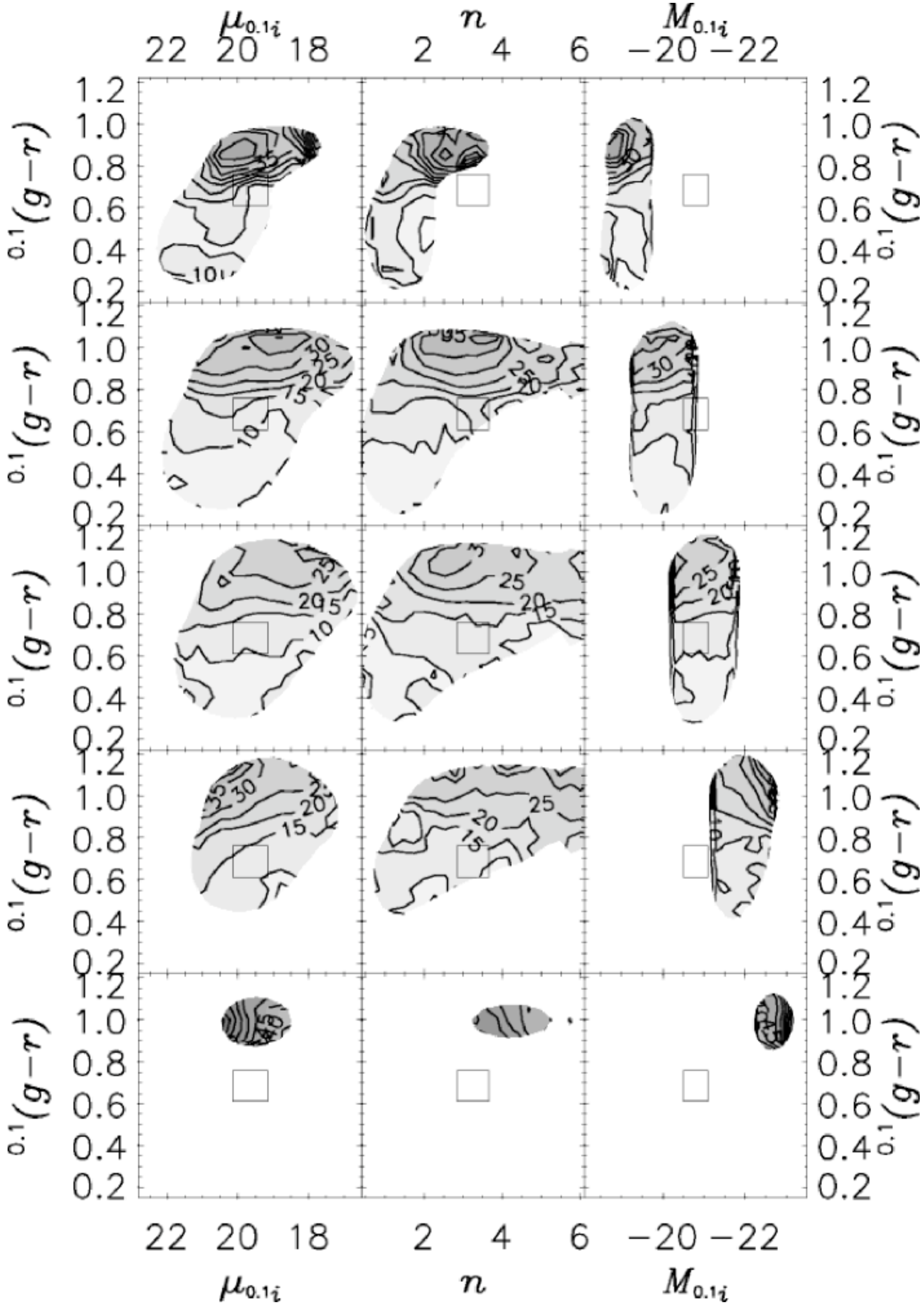
- Regions of the Universe with different local densities collapse on different time-scales.
- Galaxies in different environments have evolved with different relationships of star-formation and gravitational-collapse time-scales.
- *In principle*, observations of the differences will put strong constraints on the physics.



overdensity $\langle\delta_8\rangle$
overdensity $\langle\delta_1\rangle$
absolute magnitude $M_{0.1i}$ (mag)
$^{0.1}(g-r)$ color (mag)



(c)
1 h^{-1} Mpc
28.0
32.0
36.0
32.0
28.0
24.0
20.0
16.0
16.0
12.0
8.0
8.0
1.0
0.8
0.6
0.4
$^{0.1}(g-r)$ color (mag)
−19
−20
−21
−22
−23
absolute magnitude $M_{0.1i}$ (mag)

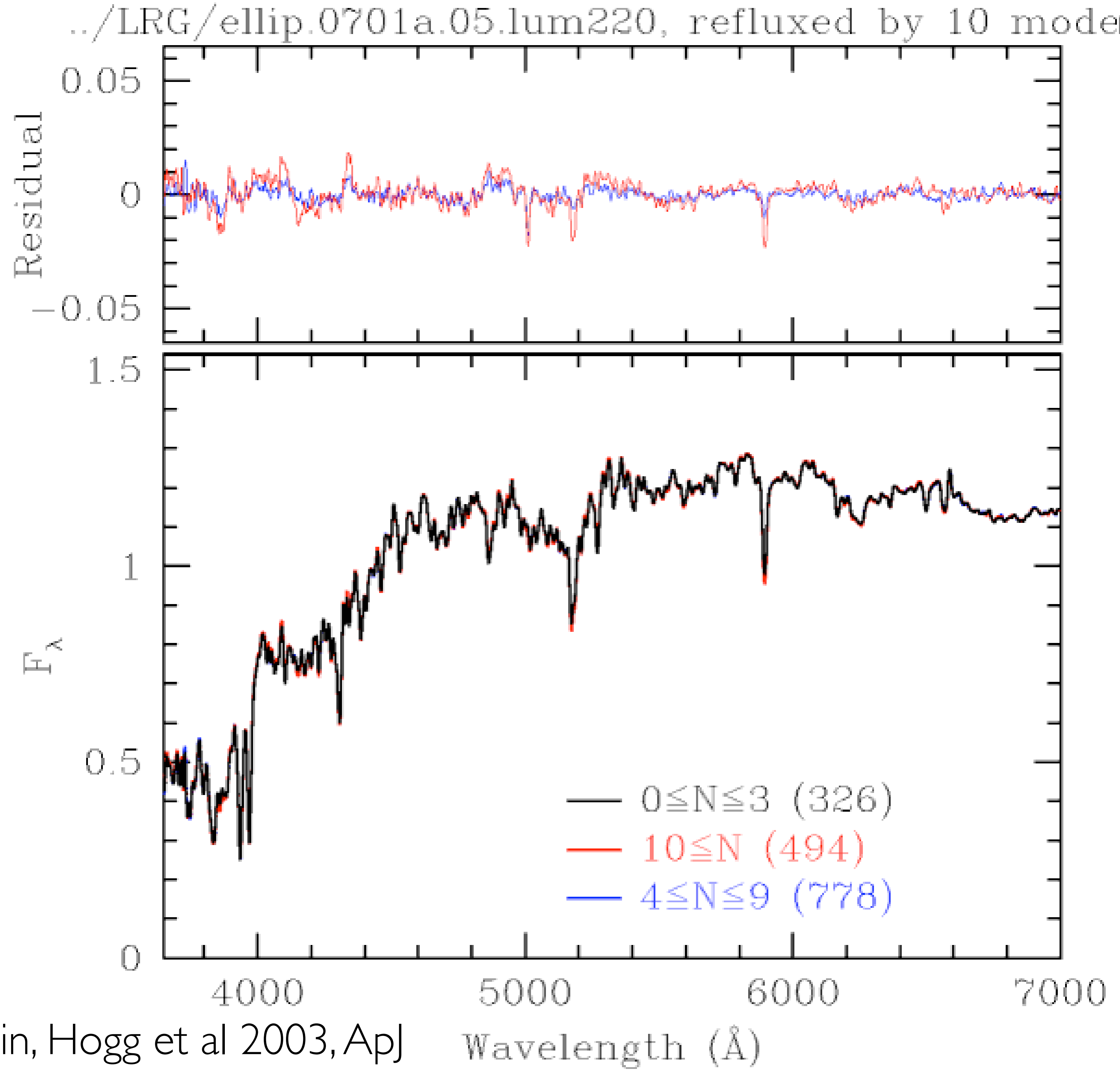


$\mu_{0.1i}$
n
$M_{0.1i}$
$^{0.1}(g-r)$

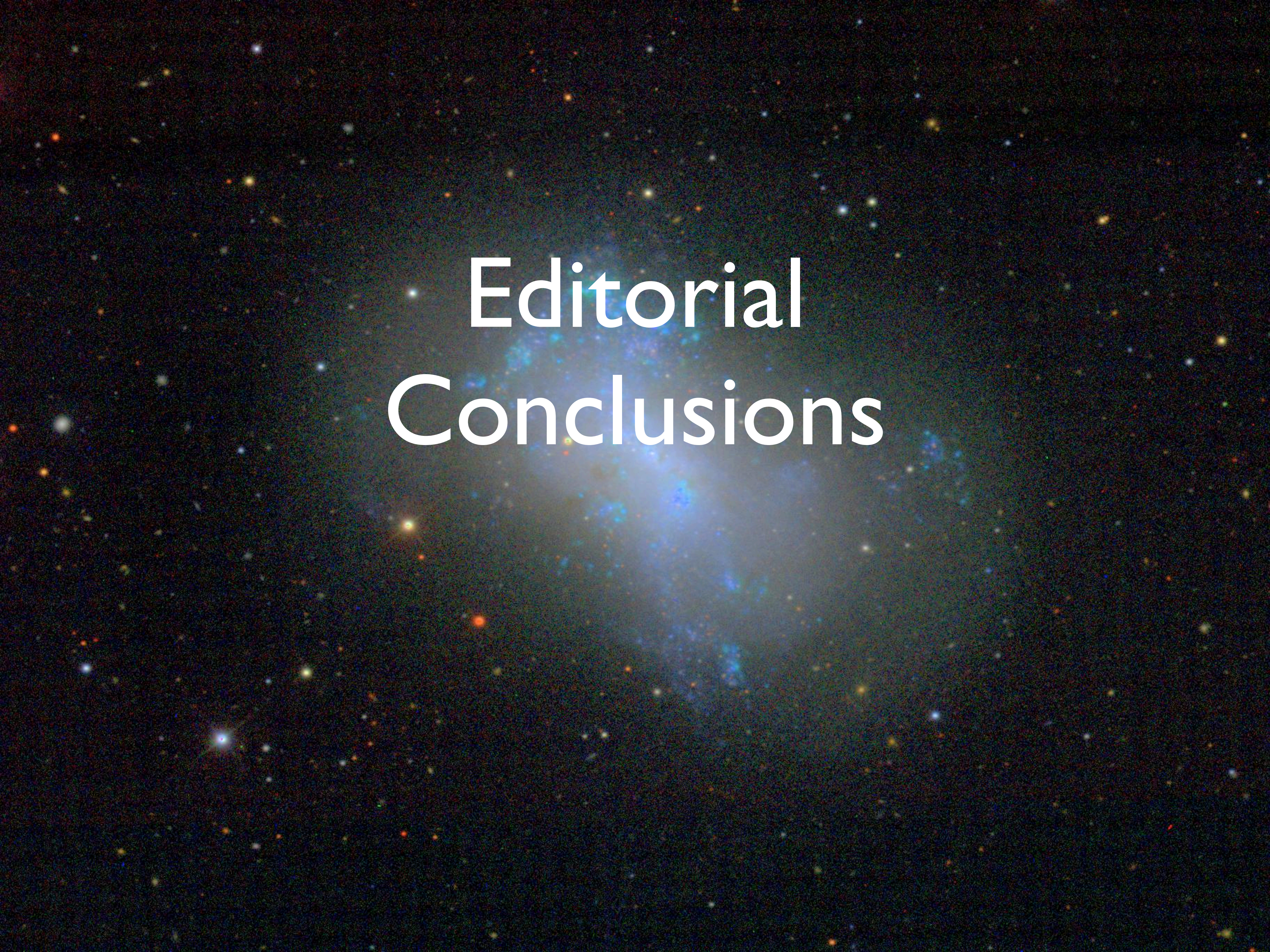
editorial comment

Galaxy environments

- Star-formation rate appears to be the galaxy property most directly tied to environment.
- What about the morphology-density relation?
- Morphology must *follow* star-formation?



Eisenstein, Hogg et al 2003, ApJ



Editorial Conclusions

editorial comment

Theory

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thank you

initial disk metallicity of [Fe/H] = −0.72 dex. Using the chromospheric activity and the stellar rotation as indicators of aging of a star, Barry (13) has derived an AMR based on a sample of about 120 stars. There are large uncertainties in the determinations of the age; nevertheless the points are consistent with the above plot for the AMR, except for the clear signature of a lull in the SFR about 3 Gy ago (169, 213, 217, 267). The AMR

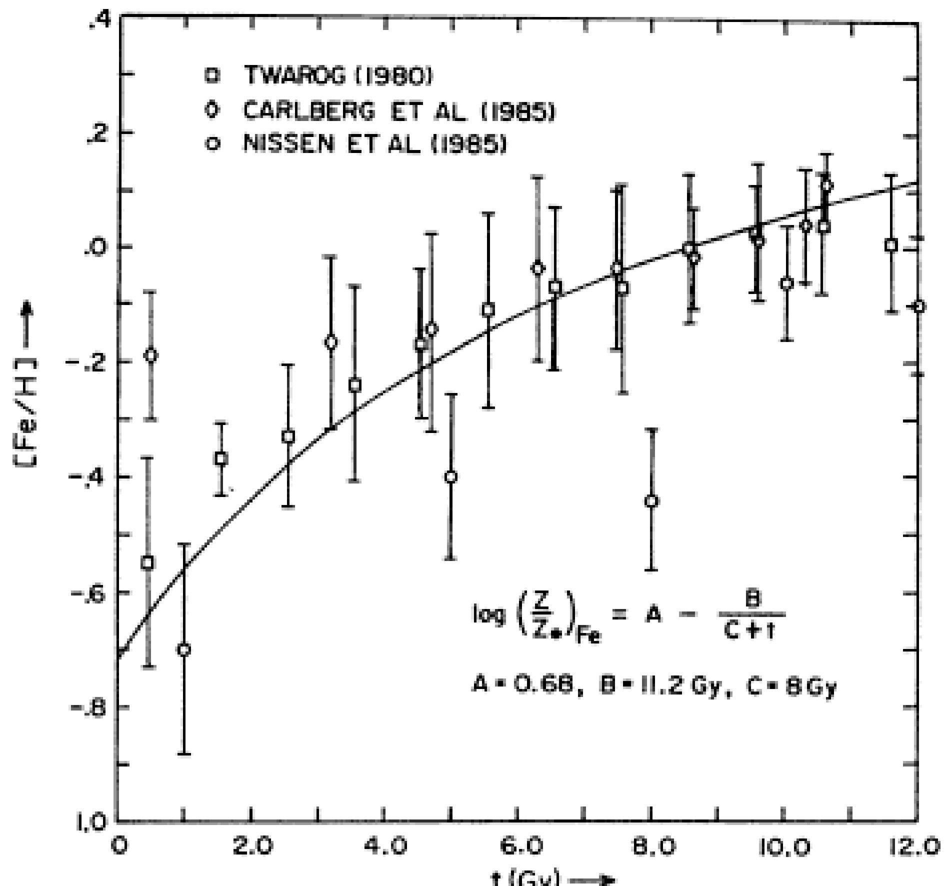

Figure 1 The age-metallicity relation for the local dwarf stars of the thin disk with the fitted curve given by Equation 2.